

Applications with Intense OTR Images I: 120-GeV Protons^{*}

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Abstract. Although the optical transition radiation (OTR) mechanism has been used in many electron-beam imaging applications, proton-beam applications have been somewhat limited. One needs both a high charge intensity and a high-gamma beam so the OTR can be collected with reasonable efficiency. In the case of the accelerator complex at Fermi National Accelerator Laboratory (FNAL), the main injector generates a 120-GeV proton beam with an intensity of $\sim 5 \times 10^{12}$ for bombardment of the antiproton production target. This option satisfies both criteria, and the OTR is so bright that attenuation by 1000 with neutral density filters was needed to avoid saturating the CID camera when a 20- μ m thin foil was used as the converter screen. Based on this success, OTR stations are being planned for the antiproton transport line to the Tevatron to assist in evaluating beam match and emittance. The ultimate goal is to improve the collider luminosity in Run II by optimizing the antiproton beam optics. Foil damage and radiation damage issues in this environment will also be briefly addressed.

INTRODUCTION

Characterization of particle beam properties in accelerators and transport lines is often important to the experiment's success. At Fermi National Accelerator Laboratory (FNAL) the beam match within the complex in support of the proton/antiproton collider program (Run II) is a critical contributor to the final luminosity at the interaction point. As a complement to present multiwire beam profiling techniques, we have explored the possibility of using optical transition radiation (OTR) techniques for imaging protons and antiprotons. Many labs have used OTR with electron beams of high energy and intensity, but the same principles apply to proton beams [1-3]. One needs more specifically high-gamma beams, and we have this situation in the FNAL complex where the main injector (MI) generates a 120-GeV proton beam with an intensity of up to 4.7×10^{12} protons in a 1.6- μ s spill. This situation results in intense OTR images such that attenuation by 1000 with neutral density filters was needed to avoid saturating the CID camera [4]. Based on the success of this prototype, OTR imaging stations are being planned for the 150-GeV antiproton transport line between the MI and the Tevatron and in the Tevatron itself to assist in evaluating the beam match and emittance. The ultimate goal is to improve the collider luminosity in Run II by optimizing the particle beam optics. Foil survivability and radiation damage to imaging components in this environment will also be briefly addressed.

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EXPERIMENTAL BACKGROUND

The FNAL accelerator complex includes a proton linac, 8-GeV booster, a 8- to 150-GeV MI, and the 1-TeV Tevatron where protons and antiprotons are used in the collider programs for high energy physics. A schematic of the facility is shown in Fig. 1. The prototype OTR experiments have been done in the AP-1 line in an air gap just upstream (prevault area) of the antiproton production target. Beam intensities of 5×10^{12} are available, and there is reasonable access for experimental adjustments. The system used 12- μm Ti or 20- μm -thick Al foils oriented at 45° to the beam direction.

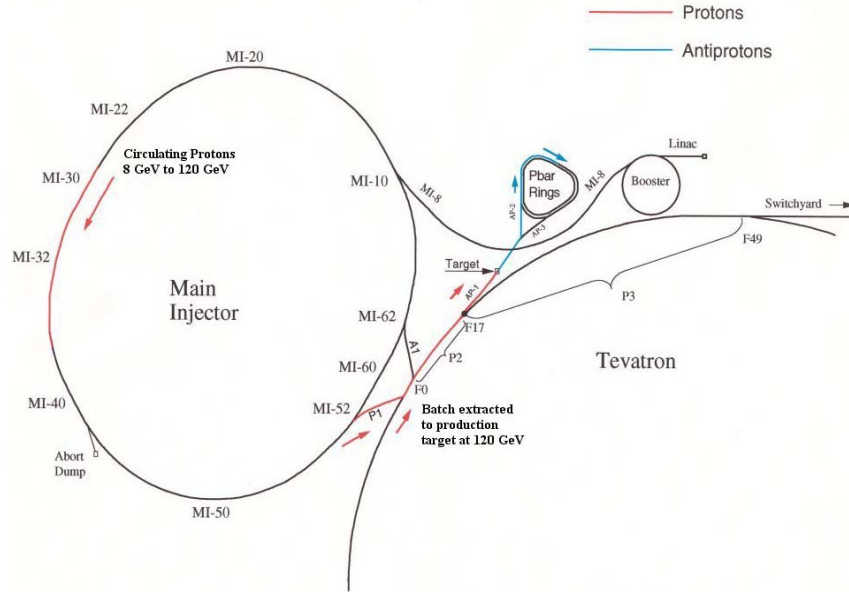


FIGURE 1. A schematic of the FNAL accelerator complex. The first experiments were done in the AP-1 line upstream of the antiproton production target.

For completeness some comments on OTR are included. Our strategy is to convert particle beam information to visible radiation and then take advantage of imaging technology and image processing programs. OTR is emitted when a charged particle beam transits the interface between different dielectric constants. The effect is a surface phenomenon that can be understood as the collapsing of the electric dipole formed by the approaching beam charge and its image charge in the dielectric at the surface. The radiation is emitted promptly in the order of tens of fs and is broadband including the visible spectrum. Its spectral angular distribution is given by [5]:

$$\frac{d^2 N_1}{d\omega d\Omega} = \frac{e^2}{\hbar c} \frac{1}{\pi^2 \omega} \frac{(\theta_x^2 + \theta_y^2)}{(\gamma^{-2} + \theta_x^2 + \theta_y^2)^2},$$

where $\alpha = \frac{e^2}{\hbar c}$ is the fine structure constant. θ is the angle with respect to specular reflection, and γ is the Lorentz factor. Typically for $\gamma = 100$ one might get 1 photon per 10^3 electrons in the visible light band. So, one key to an intense image is, of course, intense particle beams. In recent experiments at APS with electron beams we might have 10^9 particles, but the FNAL

complex has beam intensities in the 10^{11} to 10^{13} range. The other key is to have γ large enough so that the peak intensity of emissions at $1/\gamma$ can allow efficient collection of the radiation cone. For $\gamma = 100$ the opening angle is about 10 mrad so that $4/\gamma$ can be covered by a 50-mm-diameter lens at 1 meter. We use the backward OTR so the reflection coefficient of the material is involved. In this case “shiny” is better. We observed almost 4 to 5 times more light from Al foils than the Ti foils.

EXPERIMENTAL RESULTS

We performed a feasibility study for various locations in the FNAL complex [3]. In Table 1 we show that compared to the electron beam case at APS, the proton beams are larger in size, more intense, and with comparable γ at 120 GeV. In particular, the projected 2000-times-higher particle intensity made signal strength a nonissue in this case. Foil survivability, background effects of the upstream Ti vacuum window and the fluorescence of air in the gap, and radiation damage were potential issues.

TABLE 1. Possible Application of OTR Imaging to 120-GeV Proton Beams.

Feature	Electrons	Protons
Beam size (σ)	200 μm	1 mm
Macropulse	8-40 ns	1.6 μs
Q (nC)	0.3	720
Particle #	1.8×10^9	4.5×10^{12}
Gamma	10-1400	129
OTR intensity peak (Theta)	10-0.07 mrad	8 mrad

The actual initial data were recorded in August 2003 and reported first at the Fall Nuclear Science Symposium [4]. An example image is shown in Fig. 2. In this case the Al foil was used, and neutral density filter value of 3.0 was used to keep the camera from saturating with 4.7×10^{12} protons incident per TV frame time. The beam sizes of 8 mm (FWHM) and 12 mm (FWHM) for x and y planes, respectively, were measured. The OTR image is as strong as predicted, and the background halo that appears to be beam related is small but detectable. An additional background effect due to radiation damage is addressed in the next section.

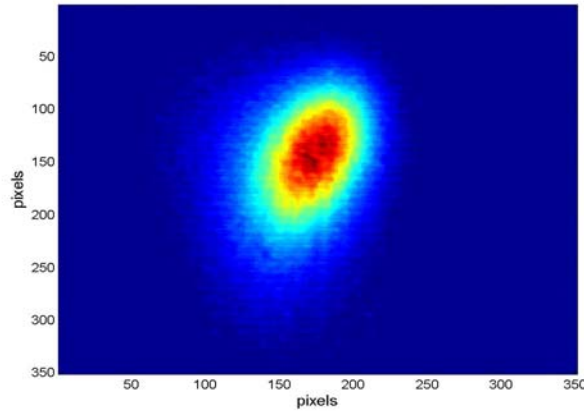


FIGURE 2. An example OTR image of 120-GeV protons using an Al foil and 4.7×10^{12} protons.

RADIATION DAMAGE ASPECTS

From the initial feasibility study, we properly anticipated signal strength was not an issue, even for 10^9 particles. However, the possible beam bombardment effects on the foils and the ionizing radiation damage effects to lenses, filters, and cameras were another reality. During the course of the prototype experiment, the A1 foil was left inserted in the beam for several months and experienced over 1×10^{19} 120-GeV protons passing through it. No visible damage to the foil was observed. The lenses and camera also remained in the accelerator tunnel through these several months. The lens was noticeably darkened and the damage to the CID camera was significant as shown in Fig. 3. The left image shows the line profile taken through the image in September 2003 and the right image in April 2004. A significant increase in dark current (the background) was observed such that the dynamic range for imaging is drastically reduced. Although the CID MEGRAD1 camera is rated to survive 1 MegaRad of gamma-ray exposure, its tolerance for proton or neutron damage is not necessarily the same. Radiation dose monitors indicated that one meter from the beam the dose was 6 kRad/week under normal operating conditions. It should be noted that the activation in the AP-1 line prevault area was found to be higher than usual in the tunnel where the camera was located in an access in April 2004. It is also noted that in the projected application in the A1 transport line, particle intensity is lower by 10-20. Additional aspects were discussed at BIW'04 [6].

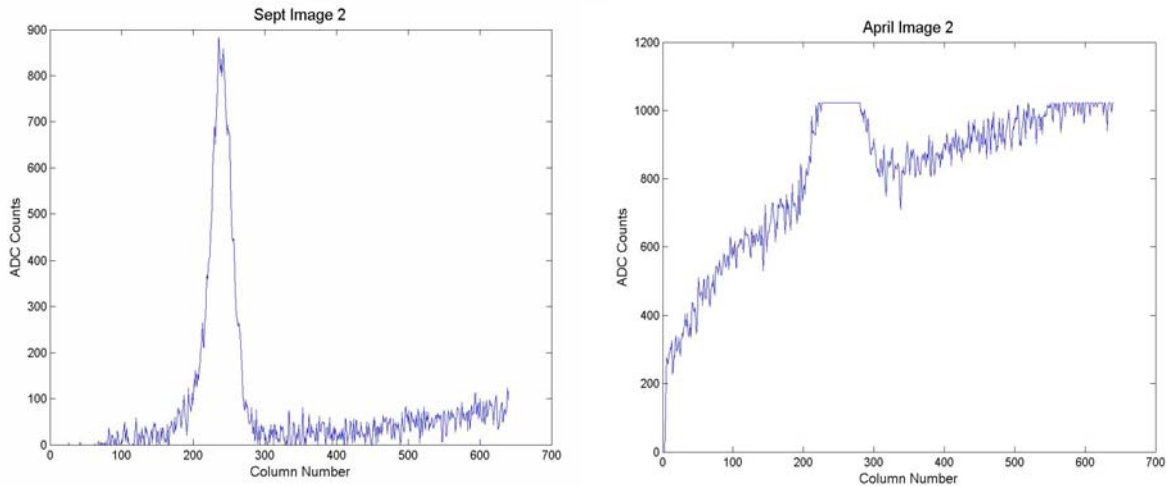


FIGURE 3. The effects of radiation damage in the dark current in the CID camera: left, September 2003; right, April 2004.

FUTURE OTR APPLICATIONS AT FNAL

Our primary interest is to assist in beam match optimization in support of Run II collider experiments. Towards this end, we are planning the installation of three OTR stations in the A1 transport line for antiprotons at 150 GeV. Antiproton beams consist of four bunches separated by 396 ns of $\sim 5 \times 10^{10}$ particles per bunch. As a part of the installation, a second foil will be selectable that allows the imaging in the same camera of reverse-injected protons ($\sim 2 \times 10^{10}$ to 5×10^{11} particles) from the Tevatron to be used to tune up the beamline optics. The station locations, lattice functions expected, and 95% beam sizes are given in Table 2. For a 95% emittance of 15π mm mrad and with these Beta functions, the anticipated sizes of the beam

envelope are 2-4 mm for the first two locations. The horizontal dispersion and energy spread product dominates the horizontal beam size at the third location. Direct comparison to a multiwire profile monitor is possible at two locations (2 and 3). We are also evaluating the possibility of using far-field imaging with the optics to measure the OTR angular distribution and to look for beam divergence effects as has been done for electron beams [7,8]. Additionally, we are adapting the system for use in the Tevatron itself for direct comparison to a new ionization profile monitor.

TABLE 2. Antiproton Transport Line to Tevatron Approximate Parameters (Extraction Tune*).

Location	Z (m)	β_x (m)	β_y (m)	D_x (m)	D_y (m)	Beam Size x-Envelope (mm)	Beam Size y-Envelope (mm)
1	~ 66	42	17	~ 0	~ 0	4	2
2	~ 76	17	44	~ 0	~ 0	2	4
3	~ 168	56	14	3.8	~ 0	10	2

* ϵ - 15 π mm mrad, 95% of particles, natural emittance

Supplementary proposals include the imaging of 120-GeV protons (3×10^{13} particles) upstream of the neutrino production target in the NuMI project. Complementary studies involve our proposals to use a gated, intensified camera to select a bunch from the antiproton pulse train; select a single turn in the Tevatron; or improve sensitivity to beam halo below the 10^9 particle point.

SUMMARY

In summary, a prototype test of OTR imaging of 120-GeV protons was very successful and corroborated our feasibility study. Radiation damage effects were observed in optics and the camera after six months and 10^{19} protons incident on the foil. The Al foil itself seemed undamaged. This is a more extreme environment than the proposed application for 10^{11} antiprotons in the A1 transport line. We will be trying thinner foils to reduce the possibility of beam scatter or loss of antiprotons, but there is a trade on foil flatness. Other possible applications are in the Tevatron itself and in a NuMI transport line. We are looking forward to direct comparison of the OTR and multiwire results and the anticipated improvement of beam match.

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